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Granulation of extruded plastic wires – influence of tool geometry and process parameters

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Abstract

Granulators cut extruded elastomer wires in small pieces, which can be used as starting raw material for injection molding. This contribution investigates the most relevant parameters of process and tool geometry for the granulation technology, with the aim of improving process efficiency and granule quality. Fiber-reinforced PA and ABS plastics have been analyzed using a dedicated test bench and finite element simulations. High-speed camera and various sensors were used to investigate the cutting process. The considered geometrical and kinematic parameters have been varied within a broad range in order to determine optimum values.

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Prof. Matthias Putz

Keywords: Cutting tool; Fiber reinforced plastic (FRP); Finite Element Method (FEM); Granulation

1. Introduction

Granulators play a key role in reducing non-brittle materials in small parts [1]. The most of those are plastics, natural substances and non-ferrous metals with various forms and geometries [2]. In recent years, great attention has been given to strand cutters because of their wide industrial use [3]. They differ significantly from the underwater pelletizers because at first the wires are water-cooled, then they are dried before being machined [4].

According to the definitions of shearing and wedge-action cutting, strand cutters combine the separation mechanism of both technologies [1, 5]. The wire is granulated by means of a rotary shear blade and a stationary anvil blade (Figure 1).

The most important kinematic and geometrical parameters which characterize this machining process have already been investigated using a cutting speed of the rotary shear blade of 60-720 m/min [3]. These values are smaller than the currently used cutting speeds of modern strand cutters.

Moreover, the granulated wires were made of polypropylene, polyvinyl chloride, polyethylene and natural rubber [1, 3, 6]. In none of the available study cases it was possible to test fiber-reinforced plastic strands. Finally, up to now only purely empirical investigations of the granulation process and cutters have been carried out.

The aim of this study is to analyze the geometry and kinematics proper of strand granulators using high values of cutting speed. The tested velocities vary in a range of 500-3000 m/min according to the currently used granulation technology. The analyzed strands consist of ABS and 30% fiberglass filled polyamide 6 (PA6 GF 30) in order to have a relevant comparison between the granulation of unreinforced and fiber-reinforced plastics.

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Parallel to the experimental procedures, a first FEM simulation model is presented as a complementary research instrument.

2. Experimental

In agreement with the main features of modern granulators, a test apparatus has been planned, realized and assembled on a HSC machining center (Figure 1).

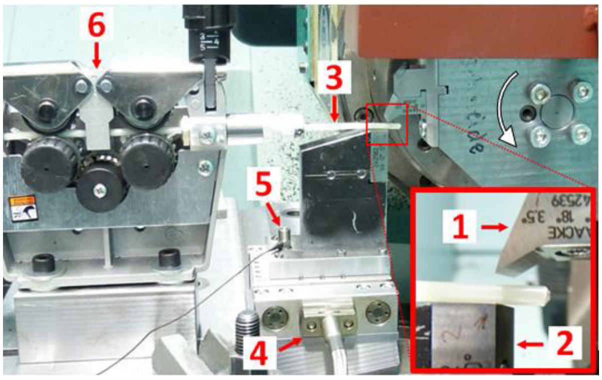

Fig. 1. Test facility: (1) shear blade; (2) anvil blade; (3) plastic strand; (4) dynamometer; (5) accelerometer; (6) wire feeder system.

The adopted cutters have a width of 15 mm because only one strand is granulated. Furthermore, the rotating blade has only one tooth. The machined wires, both ABS and PA6 GF 30, have a circular cross-section with an average diameter of 3 mm as result of an extrusion process. An appropriate feeder system has been realized by means of a modified welding wire supply device.

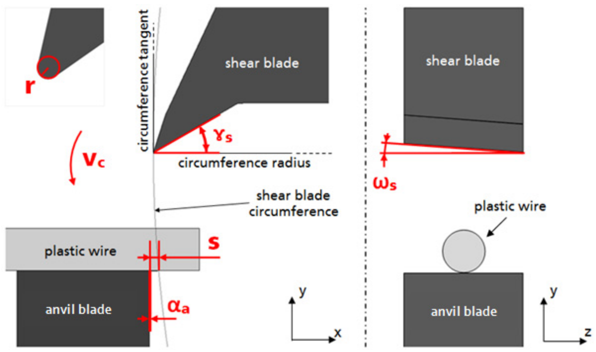

Fig. 2. Investigated process and geometrical parameters: cutting speed (v_c); tool edge radius of both cutters (r); rake (γ_s) and spiral angle (ω_s) of the shear blade; anvil blade clearance angle (α_a); cutting gap (s).

Shear and anvil blade are exchangeable in order to test different geometries. Both cutters are made of hardened alloy steel 1.2601 (HRC 60). A dynamometer and an accelerometer have been installed under the anvil with the aim of investigating the cutting forces and vibrations. Finally a high-speed camera has been integrated into the test facility.

Figure 2 shows the kinematic and geometrical parameters which mainly influence the granulation process. With reference to the defined coordinate system, cutting forces (F_c) and vibrations (a) are measured along the y axis.

The following parameters have been investigated by means of this test apparatus: cutting speed (v_c), shear blade rake angle (γ_s), shear blade spiral angle (ω_s), anvil blade clearance angle (α_a) and cutting gap (s). The investigation of the tool edge radius (r) using a test facility has not been realized because no appropriate blades were available for this purpose. The wire feed rate is adapted to the selected cutting velocity in order to obtain a constant granule length of 3 mm.

3. Finite element analysis

The program MSC.MARC® was used to develop a FE-model with some simplifications compared to the real granulation process. The model consists of a 2D representation of the longitudinal section through wire and cutters (x-y plane according to Figure 2). Besides, plain-strain and non-steady conditions are assumed. For both analyzed wire materials, an ideal elastic-plastic law with work hardening has been applied. As a consequence, the granulated wires show a purely elastic-plastic deformation without any material failure. ABS has been modelled as homogeneous material, while PA6 GF 30 has been designed as a quasi-homogeneous one with averaged properties between plastic matrix and glass fibers (Table 1).

Table 1. Material parameters for ABS and PA6 GF 30 [7-15].

Material parameter	Measurement unit	ABS	PA6 GF 30
Density	[g/cm^3]	1.05	1.35
Young's modulus	[MPa]	2100	9000
Yield strength	[MPa]	40	100
Tensile strength	[MPa]	50	154
Failure strain	[%]	20	4
Thermal expansion	[10^{-6}/K]	95	25
Thermal conductivity	[W/m·K]	0.17	0.28
Specific heat	[J/g·K]	1.3	1.5
Poisson's ratio	[-]	0.36	0.35

The following parameters have been investigated by means of this FE-model: shear blade rake angle (γ_s), anvil blade clearance angle (α_a), cutting gap (s) and tool edge radius (r).

Using this 2D FE-model it is not possible to analyze the influence of shear blade spiral angle (ω_s) and cutting speed (v_c) on the machining process. Regarding the former, it is a characteristic angle of the shear blade belonging to the y-z plane (according to Figure 1), which is not visible in the selected longitudinal section. With reference to the latter, the flow curves defined for both elastomers can be characterized by a nonlinear relationship between equivalent stress and strain occurring in the machined wire.

A variation of the cutting speed results in different strain rates and temperatures in the granulated strand. None of these aspects is visible when applying this material law.

4. Results and discussions

A reference setting for all geometrical and kinematic parameters is defined as: $v_c = 500$ m/min; $\gamma_s = 30°$; $\omega_s = 3.5°$; $\alpha_a = 0°$; s = 0.1 mm; r = 0.01 mm. These values have been determined on the basis of cutting data and tool geometry used in industry. Each parameter has been varied in a technologically feasible range (Table 2) while keeping all the others conform to the reference values. This is valid both for the experimental and for the finite element analysis.

Table 2. Investigated parameters with range and number of variations.

Parameter	Measurement unit	Variation range	Number of variation
Cutting speed (v_c)	[m/min]	500 - 3000	4
Cutting gap (s)	[mm]	0.01 - 0.7	4
Shear blade rake angle (γ_s)	[°]	20 - 50	3
Shear blade spiral angle (ω_s)	[°]	1.5 - 7	3
Anvil blade clearance angle (α_a)	[°]	0 - 40	3
Tool edge radius (r)	[mm]	0.01 – 0.5	4

Figure 3 shows the test and finite element results related to all the investigated parameters. The comparison between finite element and experimental results refers to the cutting force trends, not to their absolute values, since the FE-modeling has been realized in 2D.

An increase of cutting speed leads to higher strain rates in the granulated wire. This causes material hardening and generation of higher heat during the machining process. This in turn leads to thermal softening, which has an overcompensating impact on the material hardening for the two analyzed elastomers. According to this effect, higher cutting speed values induce sensible reduction of cutting force. Accelerations measured at the anvil are strictly dependent on the elastic deformation energy accumulated per time unit, which is significantly influenced by the cutting frequency. Increasing the cutting speed leads to higher cutting frequency on the implemented test facility. As a result, the amount of energy accumulated in the anvil per unit of time grows, thus inducing increased accelerations.

A greater cutting gap causes an increased tilt of the strand during the machining process. According to Figure 2, the force measured along the x axis increases while the cutting force (z axis) decreases. Regarding the cutting gap, only the cutting force plays a role for the change in acceleration. If the cutting force is reduced, the developed elastic deformation energy in the anvil is also decreased. As a consequence, the measured acceleration decreases.

A growth of the rake angle together with an unvaried clearance angle on the shear blade causes a reduction of the shear stress in the granulated wire, followed by a reduction of cutting force and acceleration.

A larger spiral angle causes a drawing cut with subsequent reduction of the effective wedge angle of the shear blade, thus inducing a reduction in cutting force and acceleration.
Using high values of ω_s causes, however, a wire movement along the negative z direction during the machining process (Fig. 2).

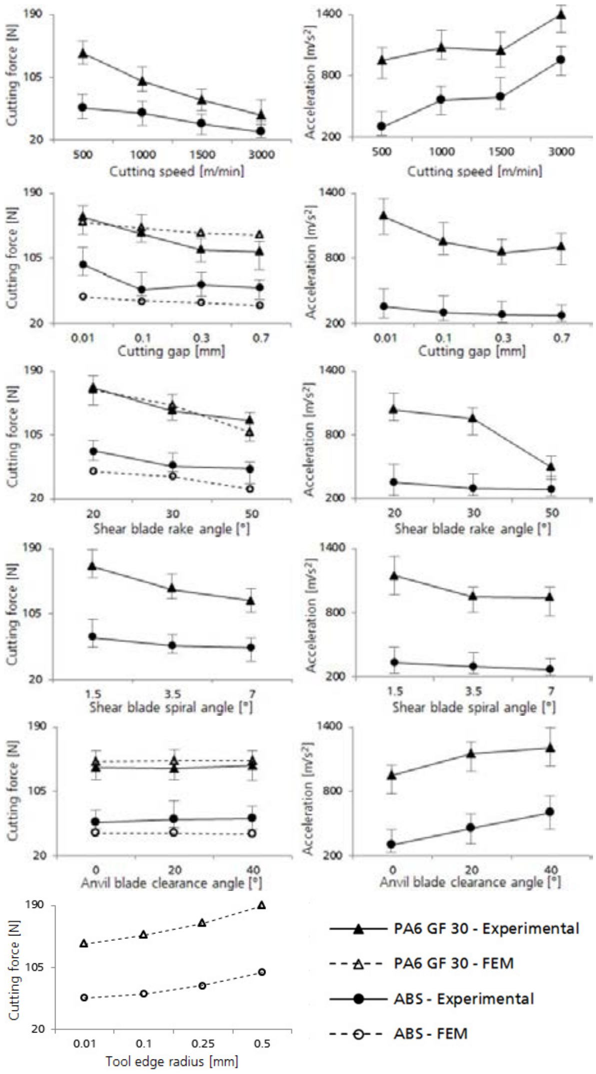

Fig. 3. Cutting force and acceleration profiles in dependency of all analyzed process and geometrical parameters.

This is an undesired effect when using real granulators, which leads to a concentration of all simultaneously machined strands on one side of the shear and anvil blades, thus causing rapid tool wear. Experience shows that a value of the spiral angle in a range of 3°-4° should prevent undesired wire movements.

During the granulation process the strand is in direct contact with the rake face and the tip of the anvil cutter. The granules impact the clearance face only after being machined. Conforming to this analysis, an increase of the clearance angle on the anvil blade does not significantly affect the cutting force. Besides, a larger clearance angle causes a reduction of the wedge angle, which results in lower mechanical stability of the anvil cutter and a higher tendency to vibrate, even though the external load is approximatively constant.

Large edge radii on both cutters cause elevated compressive stress and pinching of the machined strand, which leads to an expanded zone of high stress inside the wire itself. As a consequence, the cutting force is increased.

Figure 4 shows high speed pictures with reference to the granulation process as well as some images obtained by means of FE simulation representing von Mises stress and temperature at the time increment of maximum cutting force measured for both analyzed elastomers. As expected, temperature and stress values are sensibly higher when machining PA6 GF 30 because of its more elevated material strength.

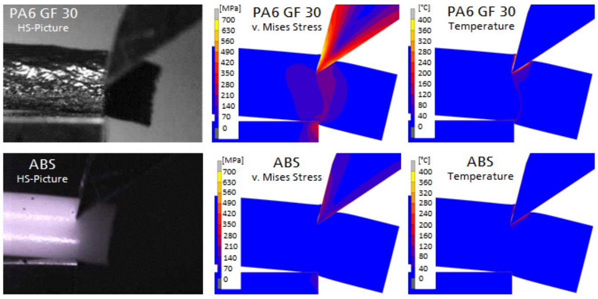

Fig. 4. High speed pictures together with thermal and mechanical load with reference to the machining of both PA6 GF 30 and ABS.

Figure 5 demonstrates the side views of the granules obtained by means of tests and FE simulation when varying the shear cutter rake angle. It is possible to distinguish a flush-cut zone and a fracture area characterizing the considered granules. For higher values of γ_s the flush-cut area increases, thus inducing smoother contours.

Small tool edge radii as well as a reduced cutting gap lead to improved granule geometry, too. After varying the cutting speed, shear blade spiral angle and anvil cutter clearance angle, no differences in the granule shapes are noticeable neither by means of FE simulation nor experimental tests.

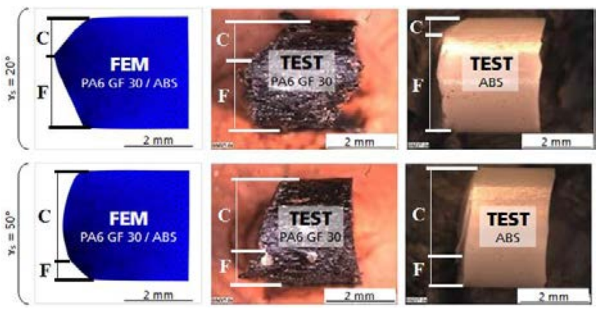

Fig. 5. Impact of shear blade rake angle on the granules shape with focus on flush-cut zone (C) and fracture area (F).

5. Conclusions

The following conclusions can be drawn from the experimental and finite element results presented in this contribution:

- High cutting speed in granulation technology is a key factor in order to reduce cutting forces. However, using elevated velocities requires a sturdy machine construction in order to avoid vibrations and noise.
- A sensible increase of shear blade rake angle leads to a reduction of cutting forces and vibrations. Besides, the quality of the granules shape is significantly improved. Enlarging this parameter involves a compromise between better granulation and lower stability of the cutting edge because the wedge angle decreases.
- An increased cutting gap between the two knives causes a slight reduction of both, cutting forces and vibrations. In contrast, the granules geometry shows evident impairment so that the gap should be rather small.
- Increasing the shear blade spiral angle induces reduced cutting forces and vibrations. On the other hand, a too large spiral angle will cause lateral drift and uneven distribution of the strands.
- A positive variation of the anvil cutter clearance angle has an irrelevant impact on cutting forces and causes higher accelerations on the anvil cutter.
- In order to significantly reduce cutting forces and to ensure high quality granules, small tool edge radii are recommended for both cutters.
- Finite element and experimental results show similar tendencies with reference to the cutting force. The developed FE model can be a reliable instrument of forecast and analysis for further investigations.
- The addition of glass fibers causes a higher material strength for PA6 compared to the unreinforced ABS.

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